Numerical simulation of transom-stern waves

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November, 22 2010

Abstract

The flow field generated by a transom-stern hullform is a complex, broad-banded, three-dimensional phenomenon marked by a large breaking wave. This unsteady multiphase turbulent flow feature is difficult to study experimentally and simulate numerically. The results of a set of numerical simulations, which use the Numerical Flow Analysis (NFA) code, of the flow around the Model 5673 transom stern at speeds covering both wet- and dry-transom operating conditions are shown in the accompanying fluid dynamics video. The numerical predictions for wet-transom and dry-transom conditions are presented to demonstrate the current state of the art in the simulation of ship generated breaking waves. The interested reader is referred to Drazen et al. (2010) for a detailed and comprehensive comparison with experiments conducted at the Naval Surface Warfare Center Carderock Division (NSWCCD).

1 Computational Method

The Numerical Flow Analysis (NFA) code provides turnkey capabilities to model breaking waves around a ship, including both plunging and spilling breaking waves, the formation of spray, and the entrainment of air. A description of NFA and its current capabilities can be found in Dommermuth et al. (2007); O'Shea et al. (2008); and Brucker et al. (2010). NFA solves

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**

4. TITLE AND SUBTITLE **Numerical simulation of transom-stern waves**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Engineering Research and Development Center,Unclassified Data Analysis and Assessment Center,Vicksburg,MS,39180-6199**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
To be presented at the 63rd Annual Meeting of the American Physical Society's Division of Fluid Dynamics (DFD) Long Beach, California from November 21st to 23rd, 2010

14. ABSTRACT
The ow eld generated by a transom-stern hullform is a com- plex, broad-banded, three-dimensional phenomenon marked by a large breaking wave. This unsteady multiphase turbulent ow feature is dif- cult to study experimentally and simulate numerically. The results of a set of numerical simulations, which use the Numerical Flow Analysis (NFA) code, of the ow around the Model 5673 transom stern at speeds covering both wet- and dry-transom operating conditions are shown in the accompanying uid dynamics video. The numerical predictions for wet-transom and dry-transom conditions are presented to demonstrate the current state of the art in the simulation of ship generated breaking waves. The interested reader is referred to Drazen et al. (2010) for a detailed and comprehensive comparison with experiments conducted at the Naval Surface Warfare Center Carderock Division (NSWCCD).

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

the Navier-Stokes equations utilizing a Cartesian-grid formulation. The flow in the air and water is modeled, and as a result, NFA can directly model air entrainment and the generation of droplets. The interface capturing of the free surface uses a second-order accurate, volume-of-fluid technique. A cut-cell method is used to enforce no-flux boundary conditions on the hull. A boundary-layer model has been developed (Rottman et al. 2010), but it is not used in these numerical simulations, and as a result, the tangential velocities are free to slip over the hull. NFA uses an implicit sub-grid scale (SGS) model that is built into the treatment of the convective terms in the momentum equations (Brucker et al. 2010). A surface representation of the ship hull is all that is required as input in terms of hull geometry. The numerical scheme is implemented in a distributed memory parallel computing environment using Fortran 90 and the Message Passing Interface II (MPI2). Relative to methods that use a body-fitted grid, the potential advantages of NFA's approach are significantly simplified griding requirements and greatly improved numerical stability due to the highly structured grid.

2 Domain, Grids, Boundary and Simulation Conditions

The Model 5673 transom is shown in figure 1, and the relevant parameters, including the length of the model, the depth of the transom, and the weight, are given in Table 1.

Table 2 provides details of the transom-stern simulations, including the speed of the model, the Froude and Reynolds numbers, as well as the sinkage and trim. For 3.60 m/s (7 knots), the transom is partially wet, and for 4.12 m/s (8 knots), the transom is dry. All length and velocity scales are respectively normalized by the model's length (Lo) and speed (Uo). The number of grid cells along the x, y, and z-axes are respectively denoted by N_x; N_y; and N_z. The number of sub domains and processors along the x, y, and z-axes are respectively denoted by n_i; n_j ; and n_k. For the simulations shown in the fluid dynamics video, discussed herein, N_x, N_y, N_z = 2688, 1024, 384 and n_i, n_j, n_k = 21, 8, 6.

The width, depth, and height of the computational domains are respectively 6.0, 1.6983, 0.66667, ship lengths (Lo). These dimensions match the cross section of the NSWCCD towing tank (Drazen et al. 2010). The computational domain extends 4 ship lengths behind the transom and 1 ship length ahead of the bow. The fore perpendicular and transom are respectively located at $x = 0$ and $x = -1$. The z-axis is positive up with the mean

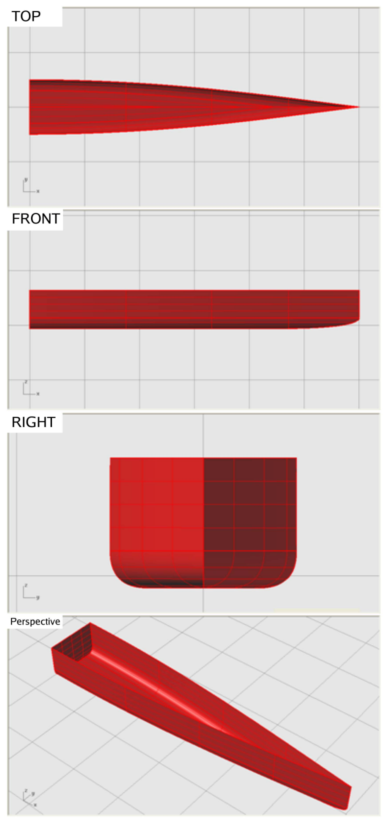

Figure 1: Model 5673. Rendered at scale. Grid line separation is 1.524 m (5 ft).

Table 1: Table 1 Model 5673 Details.

Length Overall, Lo	9.144 m (30 ft)
Waterline Length	9.144 m (30 ft)
Extreme Beam	1.524 m (5 ft)
Bow Draft	Fixed
Stern Draft, T_{max}	Variable
Construction	Fiberglass
Displacement	771.1 kg (1700 lb)

waterline located at $z = 0$. A plane of symmetry is not used on the centerline of the hull because small-scale turbulent structures are adversely affected. Grid stretching is employed in all directions. Details of the grid-stretching algorithm are provided in Dommermuth et al. (2007). The smallest grid spacing is 0.0005 near the hull and mean waterline, and the largest grid spacing is 0.01 in the far field. The numerical simulations are slowly ramped up to full speed. The period of adjustment is $To = 0.5$ (Dommermuth et al. 2007). Mass conservation is ensured using the regridding algorithm that is implemented by Dommermuth et al. (2007). Density-weighted velocity smoothing is used every 400 time steps using a 3- point filter (1/4, 1/2, 1/4) (Brucker et al. 2010). The nondimensional time step is $t = 0.00025$.

The simulations are run for 30,000 time steps, corresponding to 7.5 ship lengths, on the SGI Altix ICE at the U.S. Army Engineer Research and Development Center (ERDC). The data sets are so large that only time steps 20,0000 through 30,000 are saved every 40 time steps for the purposes of post processing. The 1.06 billion cell simulation takes about 90 hours of wall-clock time to run 30,000 time steps using 1008 processors. The wall-clock time can be cut in half by doubling the number of processors because NFA scales linearly. Alternatively, increasing the number of processors to 10,000-20,000 will enable numerical simulations of breaking ship waves and Tsunamis with 25-50 billion grid cells within the next year.

3 Flow description

The fluid dynamics video compares perspective views of laboratory and NFA results for 3.60 m/s (7 knots) and 4.12 m/s (8 knots). The 0.5 isosurface of the volume fractions are shown for the NFA predictions. The transom is

Table 2: Calculated trim angle, Froude numbers based on ship length, Fr_L, Reynolds number based on ship length, Re_L, and transom-condition.

Speed (kts)	Fr_L	Re_L	Trim (deg)	Transom (m)	Condition
7	0.38	3.29×10^7	0.48	Wet	
8	0.43	3.77×10^7	0.67	Dry	

partially wet for 3.60 m/s (7 knots) and fully dry for 4.12 m/s (8 knots). A glassy region is evident behind the transom at the 4.12 m/s (8 knots) speed. Significant air entrainment occurs for the 3.60 m/s (7 knot) case at the transom, in the rooster-tail region, and along the edges of the breaking stern wave. For the 4.12 m/s (8knot) case, air entrainment first occurs on the forward face of the rooster tail and along the edges of the breaking stern wave. For both the 3.60 m/s (7 knots) and 4.12 m/s (8 knots) speeds, the measured mean profile of the free-surface elevation agrees well with instantaneous predictions. The fluid dynamics video is available at www.saic.com/maritime/nfa.

4 Video

The full size video, mpeg4 encoded, is approximately $140Mb$ (download). The web size video, mpeg4 encoded is approximately $9Mb$ (download).

The videos are also available at www.saic.com/maritime/nfa.

SCENES:

$Fr = 0.38$**, partially wetted transom:**

1. - Stern-quartering view.

2. - Stern view.

3. - Starboard view.

4. - Stern-quartering view compared to snapshot of experiments.

5. - Stern view looking down compared to snapshot of experiments.

$Fr = 0.43$**, dry transom:**

1. - Stern-quartering view.

2. - Stern view.

3. - Starboard view.

4. - Stern-quartering view compared to snapshot of experiments.

5. - Stern view looking down compared to snapshot of experiments.

5 Acknowledgments

We would like to acknowledge Dr. Patrick Purtell with the United States Office of Naval Research for the support through ONR grant N00014-07-C-0184. We would like to acknowledge Dr. Thomas C. Fu and the NSWCCD for their collaboration and continued support.

This work was supported in part by a grant of computer time from the DOD High Performance Computing Modernization Program. The numerical simulations have been performed on the SGI Altix ICE-8200 at the U.S. Army Engineering Research and Development Center.

6 References

Brucker, K. A., O'Shea, T. T., Dommermuth, D. G., & Adams, P. (2010) Three-Dimensional Simulations of Deep-Water Breaking Waves. Proceedings of the 28th Symposium on Naval Hydrodynamics, Pasadena, California, USA, 2010.

Dommermuth, D.G., O'Shea, T.T., Wyatt, D.C., Ratcliffe, T., Weymouth, G.D., Hendrickson, K.L., Yue, D.K.P., Sussman, M., Adams, P., & Valenciano, M. (2007) An application of cartesian-grid and volume-of-fluid methods to numerical ship hydrodynamics. In the proc. of the 9th Int. Conf. on Num. Ship Hydro., Ann Arbor, MI, Aug. 5-8.

Drazen, D. A., Fullerton, A. M., Fu, T. C., Beale, K. L., O'Shea, T. T., Brucker, K. A., Wyatt, D. C., Bhushan, S., Carrica, P. M., and Stern, F. (2010) Comparisons of model-scale experimental measurements and computational predictions for the transom wave of a large-scale transom model. Proceedings of the 28th Symposium on Naval Hydrodynamics, Pasadena, California, USA.

O'Shea, T. T., Brucker, K. A., Dommermuth, D. G., & Wyatt, D. C. (2008) A numerical formulation for simulating free-surface hydrodynamics. Proceedings of the 27th Symposium on Naval Hydrodynamics, Seoul, Korea.

Rottman, J.W., Brucker, K. A., Dommermuth, D. G., & Broutman, D. (2010) Parameterization of the internal-wave field generated by a submarine and its turbulent wake in a uniformly stratified fluid. Proceedings of the 28th Symposium on Naval Hydrodynamics, Pasadena, California, USA.